CU, AU, AND ZN-PB SKARN DEPOSITS
(MODELS 18b,c; Cox and Theodore, 1986; Cox, 1986; Theodore and others, 1991)

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INTRODUCTION

The general description of skarns given below is also applicable to the SN and (or) W skarn and replacement deposits and Fe skarn deposits geoenvironmental models.

Skarns are coarse-grained metamorphic rocks composed of calcium-iron-magnesium-manganese-aluminum silicate minerals (commonly referred to as "calcsilicate" minerals) that form by replacement of carbonate-bearing rocks (in most cases) during contact or regional metamorphism and metasomatism. The majority of the world's major skarn deposits are thought to be related to hydrothermal systems (Einaudi and others, 1981). Skarns can be barren or contain metals with economic value. Skarn deposits are important sources of base and precious metals as well as tin, tungsten, and iron. Skarns are relatively high-temperature mineral deposits related to magmatic-hydrothermal activity associated with granitoid plutons in orogenic tectonic settings; skarns generally form where a granitoid pluton has intruded sedimentary strata that include limestone or other carbonate-rich rocks. The processes that lead to formation of all types of skarn deposits include: (1) isochemical contact metamorphism during pluton emplacement, (2) prograde metasomatic skarn formation as the pluton cools and an ore fluid develops, and (3) retrograde alteration of earlier-formed mineral assemblages. Deposition of ore minerals accompanies stages 2 and 3. Skarn deposits are typically zoned mineralogically with respect to pluton contacts, original lithology of host rocks, and (or) fluid pathways. Later petrogenetic stages may partly or completely obliterate earlier stages of skarn
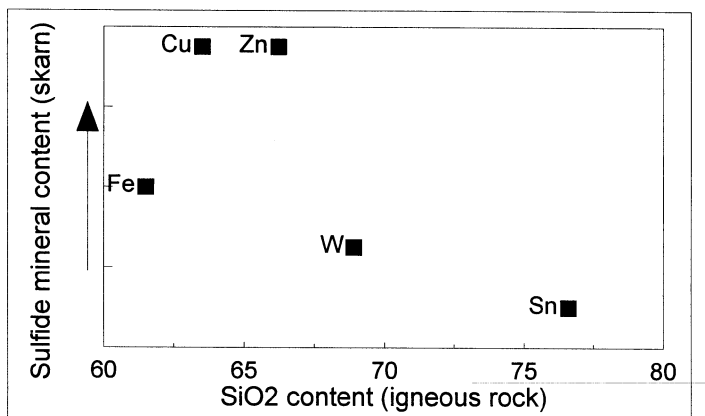
Figure 1. Schematic diagram showing relative positions of different classes of skarns as a function of associated igneous rock composition and skarn sulfide mineral content. Mean silica content, in weight percent, for igneous rocks from Meinert (1983).

that contain average ore grades greater than 1 gram of gold per tonne and are usually associated with intense retrograde alteration. Gold-bearing skarns may contain significant amounts of numerous other commodities, including copper, lead, zinc, and iron and (or) they may have been mined in the past for these or other metals.

Examples
Copper skarns: Carr Fork, Utah; Meme, Haiti; Cananea, Sonora, Mexico.
Gold-bearing skarns: Fortitude, Nev.; McCoy, Nev.; Nickel Plate-Hedley, British Columbia, Canada; Red Dome, Australia.
Zinc-lead skarns: Groundhog, N.Mex.; Bismark, Chihuahua, Mexico.

Spatially and (or) genetically related deposit types
Associated deposit types (Cox and Singer, 1986) include porphyry copper (Model 17), iron skarn (Model 18d), polymetallic vein (Model 22c) and replacement (Model 19a), placer gold deposits (Model 39a), and distal disseminated silver-gold (Model 19c; Cox, 1992).

Potential environmental considerations
Surface and ground water associated with sulfide-mineral-rich tailings and waste piles or ponds may develop elevated concentrations of dissolved iron, aluminum, lead, copper, and zinc, especially if snowmelt and rain pond in tailings areas. At some inactive and abandoned historic mine workings where tailings are dispersed into streams, aquatic and plant communities may be impacted for as much as tens of km downstream by acidic conditions and (or) elevated metal concentrations. Sulfide mineral contents for these skarns are highly variable, and sulfide minerals may represent as much as 50 to 70 volume percent in parts of some deposits.

Exploration geophysics
Local magnetic highs may indicate skarn deposits with significant abundances of pyrrhotite and (or) magnetite. Precious metal skarns that contain abundant pyrite and quartz may lack this distinctive magnetic signature. In extremely weathered terranes, exposures of limonite, iron hydroxide, iron sulfate gossan, clay, or carbonate rock associated with these deposits may be identified by analyzing spectral features on Landsat Thematic Mapper reflectance imagery. Very low frequency electromagnetic and induced polarization surveys may be used to identify magnetite and associated disseminated sulfide bodies. Resistivity surveys can be used to model the distribution of alteration zones as indicated by ion concentrations of water saturated rocks. Because of density contrasts between alteration mineral assemblages and deposit host rocks, microgravity surveys may be used to delineate the distribution of skarn deposits.

References
Geology: Einaudi and others (1981), Cox (1986), Cox and Theodore (1986), and Theodore and others (1991).
Environmental signature: Ficklin and others (1992), Smith and others (1994), Apte and others (1995), and Salomons (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Mosier (1986), Cox and Theodore (1986), Jones and Menzie (1986), and Theodore and others (1991) present deposit size ranges, expressed as percentiles of tonnages (million metric tonnes) for populations of N deposits:

Cu skarns (N=64):	0.03 (90th percentile)	0.56 (50th percentile)	9.2 (10th percentile)
Au skarns (N= 90):	0.0013 (90th percentile)	0.28 (50th percentile)	9.8 (10th percentile)
Zn-Pb skarns (N=34):	0.16 (90th percentile)		

Table 1A. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from border zone immediately surrounding Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au <0.02 oz/t; N, number of samples)]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	185	5.5	36.8	15.8
K (%)	138	.002	3.2	.41
Al (%)	185	.60	4.4	1.7
Ca (%)	185	1.1	48.2	17.5
Mg (%)	185	.15	12.8	4.1
Mn (%)	104	.007	.88	.14
Ti (%)	185	.005	.49	.11
S (%)	185	.002	30.4	3.6
Fe (%)	138	.002	32.2	5.1
Rb (ppm)	96	1	241	24
Sr (ppm)	127	36	329	125
Ba (ppm)	138	3	3,830	272
Se (ppm)	128	1	124	11
As (ppm)	135	2	2,113	96
Sb (ppm)	114	1	47	11
Bi (ppm)	138	1	200	19
Mo (ppm)	101	1	68	5
Cu (ppm)	147	100	6,900	522
Pb (ppm)	26	3	7,300	138
Zn (ppm)	262	7	14,000	207
Ag (oz/t)	250	.01	9.4	.22
Au (oz/t)	210	.001	.02	.006

Table 1B. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au ≥0.02 oz/t; N, number of samples); --, not detected]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	208	6.0	27.1	15.7
K (%)	173	.0003	4.3	.23
Al (%)	208	.7	14.3	1.8
Ca (%)	208	.21	22.1	7
Mg (%)	208	.29	13.0	2.9
Mn (%)	173	.05	.94	.19
Ti (%)	208	.0002	.47	.1
S (%)	208	.13	32.5	9.1
Fe (%)	173	.02	39.2	18.6
Rb (ppm)	173	--	85	7
Sr (ppm)	173	--	236	64
Ba (ppm)	173	--	1,289	135
Se (ppm)	173	--	169	15
As (ppm)	173	3	29,100	1,732
Sb (ppm)	173	--	47	7
Bi (ppm)	173	7	1,730	114
Mo (ppm)	130	--	19	4
Cu (ppm)	301	--	12,800	1,334
Pb (ppm)	301	8	7,400	261
Zn (ppm)	301	5	14,800	361
Ag (oz/t)	301	--	12.7	1.1
Au (oz/t)	301	.02	5.2	.36

Table 1C. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich.

[Analyses from Upper Fortitude ore zone (hosted by Middle Pennsylvanian Battle Formation; Au <0.02 oz/t; N, number of samples)]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	109	17.9	40.3	26.8
K (%)	109	.01	6.1	2.4
Al (%)	109	1.2	13.8	4.2
Ca (%)	109	.003	5.9	1.2
Mg (%)	109	.01	8.8	2.9
Mn (%)	109	.01	.18	.05
Ti (%)	109	.11	.56	.29
S (%)	109	.09	17.1	5
Fe (%)	109	2.7	22.5	8.9
Rb (ppm)	101	6	253	98
Sr (ppm)	94	31	134	65
Ba (ppm)	109	50	4,127	1,784
Se (ppm)	109	3	117	18
As (ppm)	107	2	19,700	633
Sb (ppm)	95	1	74	7
Bi (ppm)	107	2	332	63
Cu (ppm)	610	100	49,800	1,704
Pb (ppm)	614	3	8,780	147
Zn (ppm)	614	3	7,400	274
Ag (oz/t)	614	.01	9.7	.35
Au (oz/t)	614	.02	.48	.06

Table 2. Summary ranges of trace element data for some precious metal-enriched skarns in British Columbia.

[Data from Ettlinger and Ray (1989, Appendix 7). Data represent 76 samples of skarn, endoskarn, and associated rocks from skarn deposits in Banks Island, Oka, Benson Lake, Nanaimo Lakes, Dividend-Lake-view, Texada Island, and Greenwood mining districts. Analyses by atomic absorption spectrometry]

Element	Detection limit	Minimum	Maximum
Au (ppb)	20	<20	103,000
Ag (ppm)	.5	<.5	200
Cu (ppm)	10	7	193,000
Pb (ppm)	5	<5	1,500
Zn (ppm)	5	8	29,000
Co (ppm)	3	<3	17,000
Mo (ppm)	10	<10	248
As (ppm)	3 to 10	<1	445,000
Bi (ppm)	3	<3	32,000

The Copper Canyon area, Nev., (fig. 2) contains copper, gold, lead-zinc skarns whose geochemical signatures are characteristic of those associated with these deposit types. Skarn deposits in the central part of the map area (fig. 2*A*) were unexposed prior to mining. Broad areas of outcrop had elevated abundances of copper (>700 ppm) prior to large-scale mining activity (fig. 2*B*). Concentrations of lead, mercury, arsenic, and cadmium are controlled strongly

Table 3. Summary ranges of geochemical data for trace elements in fresh and variably altered rocks from northern part of New World Cu-Ag-Au district, Mont.

[Data, in ppm unless otherwise noted, from Johnson (1991, Table F-1). Samples include drill core, outcrops, and ore dumps. Fire assay and atomic absorption methods. Mean based on number of samples in which element was detected at concentrations above detection limits; --, not detected]

Element	Detection Limit	Number of Samples	Minimum	Maximum	Mean
Au	0.005	108	0.006	176	3
Cu	1	110	--	135,300	6,366
Ag	.2	105	--	300	14
Te	.2	102	--	76	6
Bi	1	85	2	1,505	46
As	5	78	<5	289	69
Pb	2	96	3	132,000	1,610
Zn	1	111	4	132,700	1,669
Ni	1	102	1	152	34
Co	1	93	1	275	22
Mo	1	94	1	62	7
Cr	1	111	2	674	105
Se	5	43	5	420	31
Hg(ppb)	5	108	<5	1,900	58
Sb	5	43	.6	580	25
W	10	46	5	316	41
Ba	20	73	30	2,200	645
Mn	1	111	--	4,670	848
Tl	.5	38	.1	2.3	.78

by surface distribution of pre- and syn-mineralization faults that acted as conduits for mineralizing fluids. Most rocks with anomalous cadmium abundances are north of the outer limit of the dispersed iron sulfide halo that surrounds almost all of the large disseminated deposits (fig. 2*F*). In addition, mercury, and to a lesser degree tin abundances, appear to be sharply zoned relative to some of the most intensely mineralized skarns (B.B. Kotlyar, unpub. data, 1995). Similar relations characterize soil geochemistry around the McCoy deposit, Nev. (fig. 3). Summary statistics for the Fortitude, Nev., gold-rich skarn in the Copper Canyon area are shown in table 1.
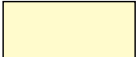
Summary ranges of trace element geochemical data for fresh and variably altered rocks from the northern part of the New World, Mont., copper-gold-silver district (Johnson, 1991), which includes the historic McLaren Mine are listed in table 3. In addition, Van Gosen (1994) analyzed 100 samples from the Homestake breccia deposit, one of five copper-gold-silver skarn and replacement deposits recently delineated by exploration in the New World district, and located less than 1 km southeast of the McLaren Mine. Van Gosen (1994) demonstrated that the Homestake orebodies are best categorized as gold-bearing skarns in the upper parts of a porphyry copper system. By comparing metal concentrations in samples of ore (Au >3,125 ppb), sub-ore (3 ppb< Au <3125 ppb), and background rock (Au <3 ppb), Van Gosen (1994) computed enrichment-depletion ratios for 24 selected metals in the Homestake deposits. Relative to background, the following elements are enriched in ore and sub-ore: Au, Ag, Cu, Mg, As, Bi, Co, Cr, Ga, Mn, Nb, Ni, Pb, and Zn. Barium, lithium, strontium, and zirconium are depleted in ore and sub-ore samples relative to background samples, whereas aluminum, potassium, sodium, titanium, and vanadium are depleted in ore samples but enriched or unchanged relative to background in sub-ore samples.

Ore and gangue mineralogy and zonation

Skarn deposits exhibit temporal and spatial zoning that reflects various stages of skarn development. Early formed prograde mineral assemblages are variably overprinted and crosscut by retrograde assemblages. Initial metamorphism forms marble and hornfels, which may be present in extensive surrounding halos. Subsequent metasomatism forms high-temperature, anhydrous calcsilicate assemblages that may be overprinted or cut by lower temperature hydrous assemblages including sulfide minerals (mainly pyrite) deposited under conditions of increased sulfur concentrations.

Cu skarns: Prograde- Pyroxene (diopside-hedenbergite), garnet (andradite-grossular), wollastonite.
                    Retrograde- Actinolite, chlorite, clay, epidote.
                    Ore- Chalcopyrite, pyrite, hematite, magnetite, sphalerite, galena, arsenopyrite; less common, bornite, pyrrhotite, molybdenite, tennantite, bismuthinite, enargite, cobaltite, and tetrahedrite.

EXPLANATION

Younger alluvium and fanglomerate deposits (Quaternary)

Altered granodiorite and quartz diorite (Tertiary)

Havallah sequence (Permian, Pennsylvanian, and Missisipian) -- In this area includes only lithotectonic unit 1 of Murchey (1990) (Permian and Pennsylvanian); argillite, shale, and chert

Antler sequence of Roberts (Permian and Pensylvanian) -- Includes conglomerate of Middle Pennsylvanian Battle Formation, limestone of Pennsylvanian and Permian Antler Peak Limestone, and sandstone and conglomerate of Permian Edna Mountain Formation

Scott Canyon Formation (Devonian) -- Chert, shale, argillite

Harmony Formation (Upper Cambrian)-- Mostly feldspathic sandstone

Geological contacts

High angle fault -- bar and ball on side of down-dropped block

Thrust fault -- sawteeth on upper plate

Outer limit of pyritized rocks, hachures on side of pyritized rock

Projection to the surface of outer limit of large disseminated deposits

Small vein deposits and occurrences

Projection to the surface in *B-F* of outer limit of :

Cu, Au, Ag altered porphyry deposits

Cu, Au, Ag skarn deposits, unexposed prior to mining, sulfide

Au, Ag (Pb, Zn, Cu) skarn deposits, exposed prior to mining, sulfide

Au, Ag (Cu, Pb, Zn) skarn deposits, oxidized, exposed prior to mining

Trend of major drainages showing stream-flow direction

Concentrations of select metals in 2,927 rock samples
(in parts per million; N.A., not applicable)

	Copper	Lead	Mercury	Arsenic	Cadmium
	<50	<10	<0.02	<200	<20
	50-150	10-70	0.02-0.2	N.A.	N.A.
	200-700	100-700	0.2-1	200-700	20-50
	>700	>700	>1	>1000	>70

Copper

Lead

NOT SAMPLED

0   N   3000 ft

97
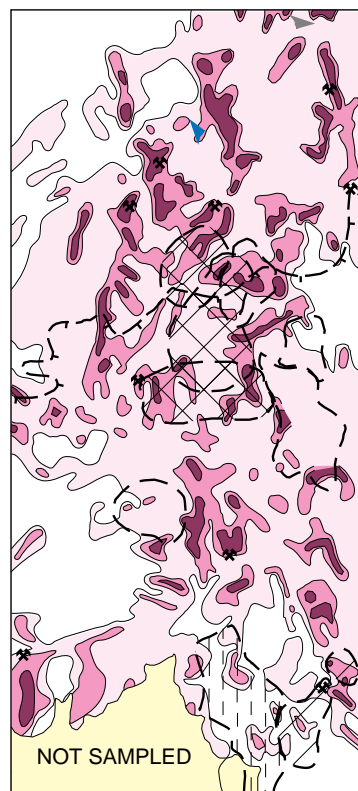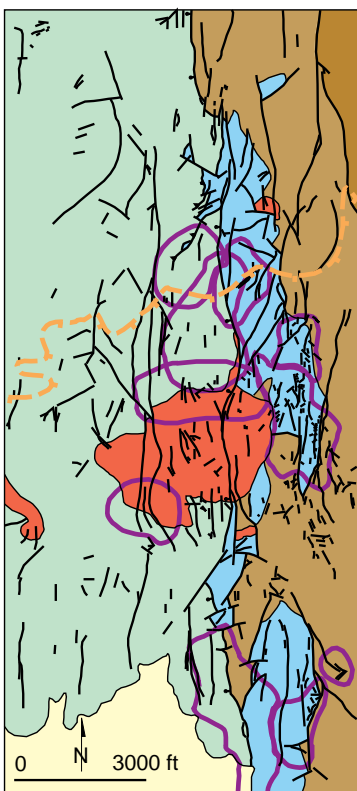
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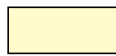
◻ Alluvium (Quaternary)

◻ Felsite porphyry (Tertiary)

◻ Granodiorite (Oligocene) -- Brown stock, 38-39 Ma

Cane Spring Formation (Upper Triassic) -- In this area includes:

◻ Limestone Member   ◻ Clastic Member

◻ Osobb Formation (Upper Triassic)

◻ Augusta Mountain Formation (Middle and Upper Triassic)
 -- In this area includes Smelser Pass Member

◻ Skarn, marble, and jasperoid   ⬭ Open pit

⌒ Contacts   ⟋ High angle fault

Concentrations of select metals in soil samples
(in parts per million; --, not detected)

	Gold	Copper	Arsenic
	<0.1	<50	<5
	0.1-0.2	50-100	5-10
	0.2-0.3	100-200	10-15
	0.3-0.4	200-300	15-20
	>0.4	>300	

McCoy Area

GOLD - SOILS

COPPER - SOILS

ARSENIC - SOILS

Au-bearing skarns:	Prograde—Garnet (andradite-grossular), pyroxene (diopside-hedenbergite), idocrase, wollastonite.
	Retrograde—Epidote, amphibole, chlorite, prehnite, scapolite, boron minerals, potassium feldspar, clay, siderite.
	Ore—Gold (electrum), pyrite,pyrrhotite, chalcopyrite, arsenopyrite, magnetite, hematite (specularite), sphalerite, galena, bismuthinite or native bismuth, hedleyite, telluride minerals, molybdenite, and scheelite; gold is present as native gold or electrum associated with pyrrhotite, chalcopyrite, or with quartz-pyrite assemblages.
Zn-Pb skarns:	Prograde—Pyroxene (hedenbergite-johannsenite), garnet (andradite-spessartine), bustamite, rhodonite.
	Retrograde—Actinolite (Mn-rich), ilvaite, chlorite, dannemorite, rhodochrosite, epidote.
	Ore—Sphalerite, galena, pyrrhotite, pyrite, magnetite, chalcopyrite, arsenopyrite; manganese-rich silicate and carbonate minerals are a distinctive characteristic of Zn-Pb skarn deposits.

Mineral characteristics

Ore may be present in sulfide-mineral-rich, massive lenses or pods or it may be disseminated. At the Nickel Plate mine in Canada, <25-micron-diameter grains of native gold associated with hedleyite are adjacent to arsenopyrite and gersdorfite. In other parts of the same deposit, electrum is concentrated in microfractures in and around chalcopyrite, pyrrhotite, sphalerite, and bismuth (Ettlinger and Ray, 1989). In contrast, gold at the McCoy, Nev., skarn is spatially and paragenetically associated with late-stage pyrite and forms 20- to 100-micron-diameter grains

bordering pyrite cubes. Mineral characteristics in skarns are likely to vary considerably within a single deposit due to the zoned nature of skarns and replacement of early-formed minerals by later mineral assemblages. In zinc-lead skarns, ore commonly forms massive pods of pyrrhotite, sphalerite, galena, and chalcopyrite in pyroxene zones.

Secondary mineralogy

Gossans develop over sulfide-mineral-rich parts of skarn deposits and may concentrate metals. Manganese oxide rich gossans are associated with zinc-lead skarns. Supergene alteration (oxidation) leads to formation of clays, hematite and goethite (after pyrite and other sulfide minerals), and secondary copper minerals (after chalcopyrite). Gold-rich skarn at the McCoy, Nev., deposit is highly oxidized and argillized to as much as 245 m below the present surface (Brooks and others, 1991). Minerals in these argillized zones include a variety of clays (montmorillonite, nontronite, smectite, and illite), manganese oxide minerals, supergene copper oxide minerals, claudetite (As_2O_3), willemite (Zn_2SiO_4), marcasite, and hydrated iron oxide minerals. At the Red Dome Au skarn deposit in North Queensland, Australia, high-grade gold ore is concentrated in highly oxidized karst-collapse breccia which formed during post-mineralization uplift and erosion; oxidation of primary tellurium-rich hypogene sulfide ore promoted karst formation and concentration of free gold (Torrey and others, 1986). Mineralogy and zoning that develops during supergene alteration of zinc-lead-silver sulfide ore in carbonate rocks depends on local Eh and pH conditions, permeability, and relative activities of carbonate species and sulfate ions in leaching ground water (Sangameshwar and Barnes, 1983). For example, cerussite is the first lead mineral to precipitate where dissolved carbonate is more abundant than sulfate, but anglesite precipitates if the situation is reversed. Supergene minerals associated with copper-lead-zinc-silver ore include azurite, malachite, smithsonite, cerargyrite as well as cerussite, anglesite, manganese minerals (pyrolusite, groutite), goethite and sulfide mineral products from bacterial reduction.

Topography, physiography

Skarn deposits in the western conterminous United States typically are present in mountainous areas, but can be present in a variety of settings; some are buried in fault blocks under Tertiary or Quaternary basin fill. Skarns also may be present in roof pendants in plutons, as well as at contacts with plutons. These types of skarns are in continental margin, syn- to late-orogenic tectonic settings such as those exposed in British Columbia, Peru, Japan, and the western Cordillera of the United States and Mexico.

Hydrology

In some deposits, shear zones and faults are important structural controls for channeling hydrothermal fluids and subsequent mineralization. In other deposits, lithologic contacts serve as fluid conduits. Post-mineralization faults may also channel fluids. At Minera Bismark, a zinc-lead skarn deposit in northern Mexico, water flows continuously along a major post-mineralization fault, as well as along other faults and fractures in granitic rock, necessitating a pumping system to dewater the orebody (Mining Magazine, 1994). Ferricrete deposits represent iron remobilized from weathered sulfide minerals by surface and subsurface water and indicate locations of former springs or drainage seepages. Manganese or iron bog deposits may provide clues to paleohydrology in the vicinity of base and precious metal skarn deposits. Faults at Copper Canyon, Nev., are known to have channeled ground water for several km during periods of enhanced ground-water availability.

Mining and milling methods

These deposits have been exploited by open pit and underground mining methods. Copper-gold ore is milled primarily by gravity and flotation methods. Copper is usually recovered by flotation. Gold is commonly recovered by cyanide leaching of crushed ore using carbon adsorption, carbon stripping at elevated temperatures and pressures, electrowinning and refining to produce dore bullion. Crushed ore may be agglomerated with cement and lime before leaching to stabilize it and promote thorough leaching. A new pyrite flotation process is available as a substitute for cyanide processing of pyrite-rich gold ore to produce tailings that have negligible acid generation potential. Resulting gold-rich pyrite concentrates are dewatered and shipped to smelters for refining. Differential flotation and separation processes are used to recover metals from complex polymetallic ore (for example, the zinc-lead skarn at Minera Bismark, Mexico) after crushing and milling to produce concentrates for shipment to smelters.

ENVIRONMENTAL SIGNATURES

Surface disturbance

Surface disturbance associated with mining these deposits is variable. Historic deposits were typically mined by hand

Table 4A. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Surface water stations and ground water observation wells.

[The McLaren open pit mine and mill operated from 1934 to 1953. Data compiled from reports cited in SCS Engineers, 1984; N, number of observations; flow, in cubic feet per second; SC, specific conductance in micromhos/cm; other measurements in mg/l. Samples were collected and analyzed in 1973 to 1975 and in 1983. N.d., not determined]

Parameter measured	Ground water analyses			Surface water analyses		
	N	Minimum	Maximum	N	Minimum	Maximum
Flow	N.d.	N.d.	N.d.	21	0.06	293
pH	47	2.22	8.03	29	3.69	8.17
SC	47	103	26,300	29	104	1,480
Acidity	16	123	13,200	9	14.2	176
Alkalinity	42	0	469	24	0	118
SO_4	42	1.6	49,900	25	7.2	854
Si	41	2.2	62	25	5.6	29.6
Fe[1]	20	<.02	3,660	10	0.09	143
Fe[2]	42	<0.03	20,600	24	<0.03	198
Al	35	<0.1	21.4	21	<0.01	4.56
Pb	24	<0.02	0.74	19	<0.003	0.07
Cu	23	<0.01	15.93	21	<0.01	0.5
Zn	22	<0.01	2.69	20	<0.005	0.3
Cd	23	<0.02	0.1	19	<0.001	0.02

[1] Total recoverable iron
[2] Total dissolved iron

Table 4B. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Total recoverable metals in mine and mill site drains; measured in September, 1979. Data in mg/l.

[--, not detected]

Parameter measured	Mine site	Mill site
pH	4.5	5.0
Cu	3.56	--
Zn	0.14	0.12
Fe	33.7	17.2
Mn	1.01	2.94

in underground workings. Multiple adits, pits, and tailings piles are commonly present at inactive and abandoned workings because skarn deposits were often explored or worked at different sites, and at different times in the past, along limestone-pluton contacts. Placer gold workings are downstream from many gold-bearing skarn deposits. Some placer gold workings have affected areas of as much as 5 km^2.

Drainage signatures
Analogies with mine drainage compositions for polymetallic replacement deposits characterized by pyrite +chalcopyrite + sphalerite + galena veins or replacements in carbonate-rich host rocks (for example, Leadville, Colo.), indicate that mine drainages are likely to exhibit near-neutral pH ranges, carry moderate concentrations of dissolved metals (10 to 100 mg/l total Zn+Cu+Cd+Pb+Co+Ni), but may contain elevated (as much as 100,000 mg/l) amounts of zinc. Dissolved aluminum and iron concentrations are both likely to about 100 mg/l, but can be much less (Smith and others, 1994). Parts of deposits that are not in contact with carbonate rocks may cause associated drainages to be more acidic and metal rich. See tables 4 and 5 for examples of compositions of surface and ground

Table 5. Chemical analysis of a water sample from the Cananea Cu skarn deposit, 275 m level, Sonora, Mexico; all data in mg/l. [Data from White and others (1963, Table 24). Water affected by oxidation of disseminated sulfide minerals]

SiO_2	56
Al	22
Fe^{2+}	524
Mn	153
Cu	60
Zn	252
Ca	753
Mg	86
Na + K	198
SO_4	4,460
Cl	22

water associated with selected sulfide-mineral-rich copper skarn deposits. These data indicate total recoverable metals and, therefore, provide no information concerning dissolved versus suspended metals or metal speciation. Seasonal fluctuations affect flow and pH in some climates, especially where snow melt affects surface water during summer months (fig. 4). Various parameters of surface and ground water from monitoring sites in the New World, Mont., copper-silver-gold district are plotted in figure 5. These sites are on, or immediately adjacent (within 100 m) to, an 87,000 km^3 tailings pile removed from the mine site. These data (table 4A) for water samples collected in the 1970s and early 1980s (SCS Engineers, 1984), reflect signatures that developed from mine tailings at a mill site for ore from the McLaren mine, a skarn that was worked as an open pit mine from 1934 to 1953. At the time of the analyses, a stream flowed directly over part of the tailings pile. The stream ran red and was impacted for about 16 km. The stream contained no fish and was characterized by reduced benthic organism populations mainly due to high dissolved iron and relatively high aluminum concentrations. Rock geochemical data (table 3) from the New World district include samples from in and around the historic McLaren mine. Water data from mine and mill site drainages are cited in table 4B. Many surface and ground water samples have near-neutral pH values (6 to 8). Specific conductance (a measure of dissolved solid content), iron, and to a lesser extent aluminum, all increase dramatically with decreasing pH (fig. 5). Sulfate concentration increases with increasing specific conductance (fig. 5) in both surface and ground water. However, ground water has much higher sulfate concentrations and specific conductances than surface water for the same pH ranges (note the difference in scale on fig. 5). These same data are plotted on a modified Ficklin diagram to show base metal abundance ranges as a function of pH (fig. 6). Note that the original Ficklin diagram (Ficklin and others, 1992) was devised to show the variations in aqueous (not total) base metal concentrations for systematically sampled water draining diverse ore deposit types in Colorado and included nickel and cobalt. Nevertheless, the New World water data mainly plot (fig. 6) in the near-neutral to acid, low to high metal fields and are much less acidic than water that drains many other deposit types. As Ficklin and others (1992) noted, the ability of carbonate-hosted deposits to generate metal-rich water appears to be a function of sulfide mineral content. The unusually high pyrite content of skarn ore at New World, along with the unusual situation of stream flow directly over tailings, led to some relatively high metal abundances in water on a local scale. However, iron and aluminum, not base metals, were cited as the primary pollutants during a U.S. Environmental Protection Agency (EPA) investigation. Many skarns in Nevada, however, are in semi-arid to arid climatic environments where annual rates of evaporation exceed annual rainfall and commonly most stream flow is intermittent.

A variety of samples, including stream sediment, heavy-mineral concentrates, soil, pond and spring mud, and iron-rich stream and mine adit flocculent precipitates, were collected in September, 1993, as part of a geochemical baseline study of the New World, Mont., district and adjacent areas (R.R. Carlson and G.K. Lee, unpub. data, 1995). In addition, *in-situ* pH and conductivity readings of water in streams, ponds, springs, seeps, and mine
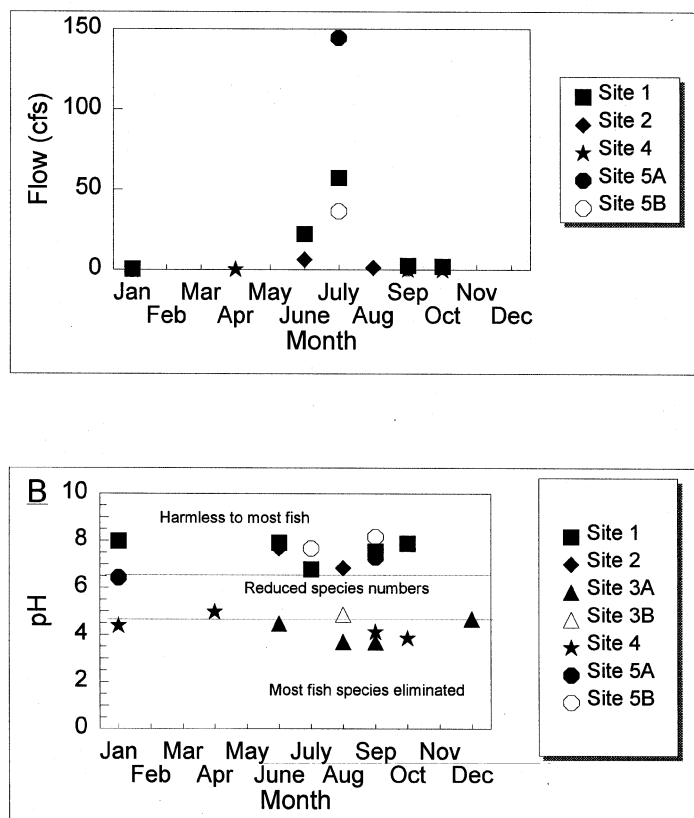
Figure 4. Seasonal variations in *A*, stream flow and *B*, pH for surface water from monitoring sites adjacent to a tailings pile at an historic mill site along Soda Butte Creek in the New World, Mont., district. These data reflect impacts caused by a tailings pile failure rather than drainage from a mine. The tailings were removed from the McLaren copper-gold-silver mine and placed at the mill site several km south of the mine. Two data sets, which represent sampling in 1974 (a) and 1975 (b), are plotted for sites 3 and 5. Dashed lines on *B* separate pH ranges in terms of generalized effects of pH on aquatic ecosystems (based on Potter and others, 1982). Note that the average pH value for precipitation in this area is 5.3. Water data from SCS Engineers (1984).

adits and open pits were made. Figure 7 is a preliminary contour map of pH ranges generated from the unpublished data and augmented by data from the National Uranium Resources Evaluation (Broxton, 1979). Areas characterized by high acidity (pH <5) represent water in a variety of settings. pH values in the area at the southeast end of Henderson Mtn. represent standing water in an inactive open-pit mine and low-volume seeps down hill from the pit. pH values for the area in the headwaters of the Stillwater River represent water draining recontoured mine waste rock. Most of the low pH values in the upper reaches of Fisher Creek represent discharge from abandoned adits; the remainder of these low pH values represent spring water. In all cases, highly acidic water appears to be ameliorated to near-neutral pH, probably as a consequence of buffering by water draining limestone and calc-alkaline intrusive rocks of the New World area, within 1000 meters of source areas.

In natural water, free metal ions such as Cu^{2+} are the most bioavailable and most toxic aqueous species; however, complexing with dissolved organic matter greatly reduces bioavailability.

Metal mobility from solid mine wastes

Oxide zone mine waste from skarn deposits may pass environmental monitoring tests for static acid generation potential and mobilization, whereas sulfide mineral zone wastes from the same deposit may fail such tests.

The mobility of metals from solid mine waste (tailings) varies as a function of pH, Eh, and the composition of tailings. Pathways for metal release from tailings include structural failure of tailings (for example, during a flood), direct discharge of tailings into surface water, dust, concentration in plants, erosion, and leaching into ground water (Andrews, 1975). The presence of sulfide minerals, especially pyrite, in tailings exposed to oxidation promotes development of acid mine drainage and concomitant metal mobility if carbonate mineral content and dissolution rates in tailings are insufficient to neutralize sulfide mineral oxidation (Ripley and others, 1995). Although carbonate rock
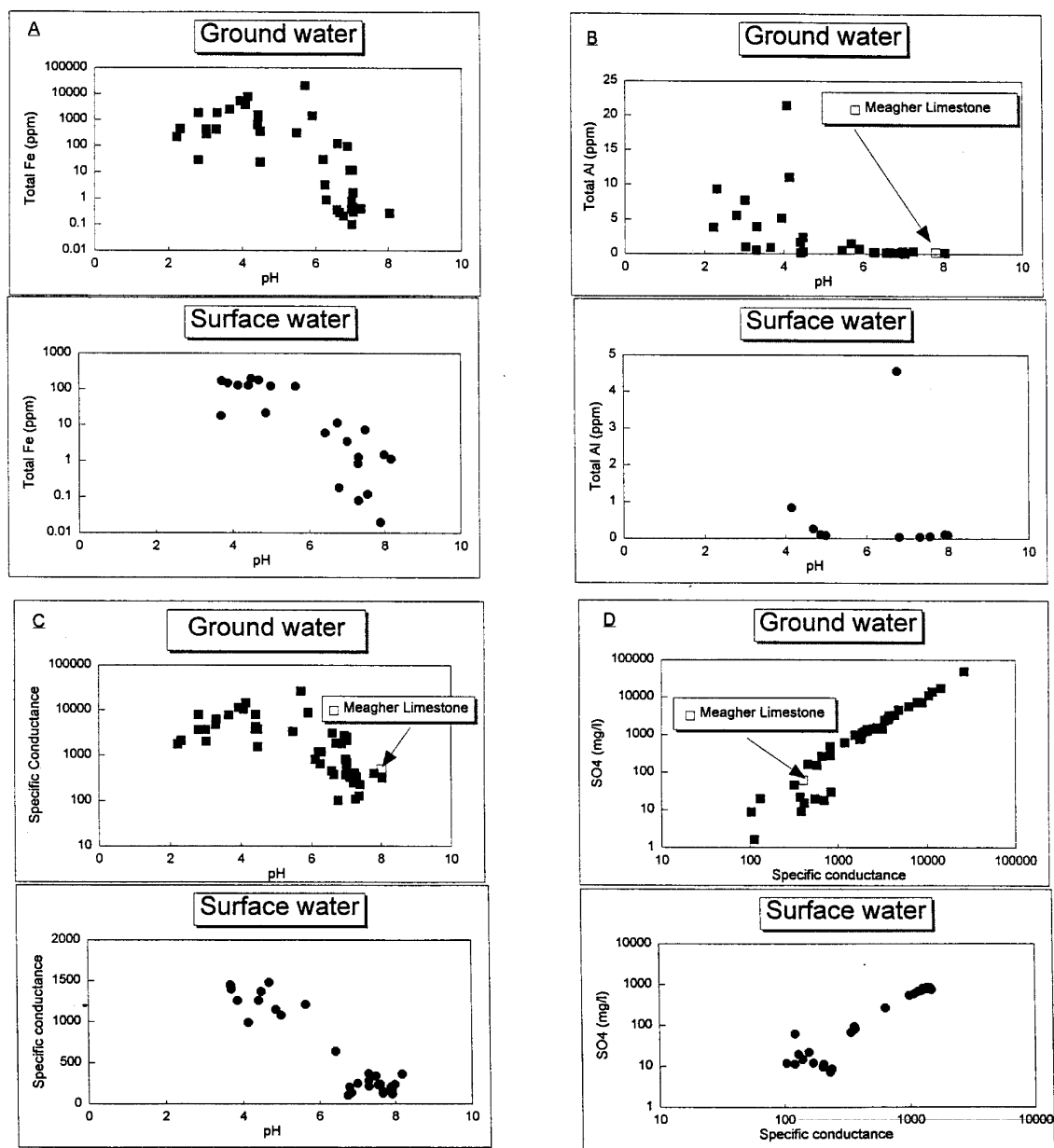
Figure 5. Plots showing *A*, relationships between pH and iron abundances; *B*, pH and aluminum abundances; *C*, specific conductance and pH; and *D*, between sulfate abundances and specific conductance for ground (squares) and surface (circles) water in the New World district, Mont. Water data from SCS Engineers (1984). Ground water chemistry for Middle Cambrian Meagher Limestone (at Ennis, about 130 km north-northwest of the New World district) reported by White and others (1963, table 6) is shown for reference (open square). The Meagher Limestone is the most important host rock for skarn deposits in the New World district (Johnson, 1991).

is commonly present in skarn deposits, waste rock may include less reactive gangue minerals, including silicate minerals, and tailings may have highly variable acid-buffering capacity. Andrews (1975) reports typical abundances for a number of metals, including 6 to 38 ppm lead, 10 to 65 ppm zinc, and 1 to 35 ppm copper, in tailings associated with a number of deposit types.

Metals released from weathered primary (hypogene sulfide ore) and secondary (supergene oxide and sulfide) minerals in tailings at the Kelley zinc-lead skarn deposit in the Magdalena, New Mex., district are fixed by precipitation of tertiary minerals and by ion exchange into phyllosilicate minerals on grain surfaces and along
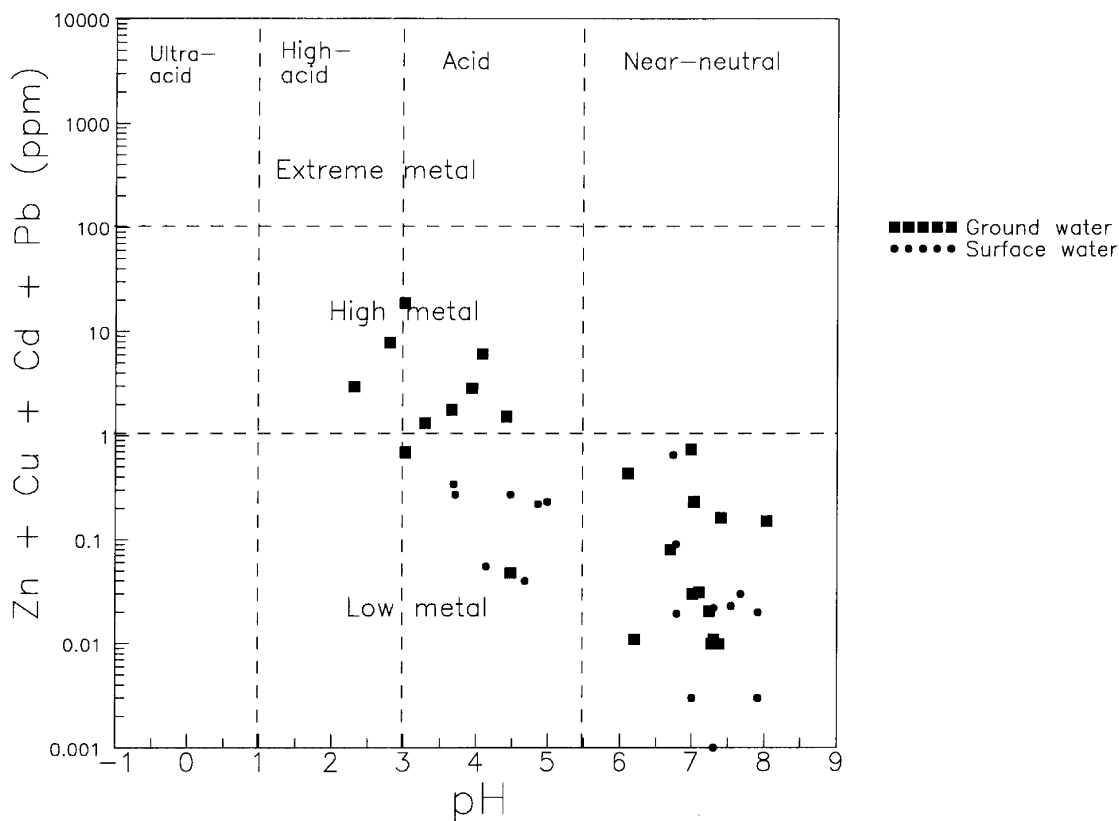
Figure 6. Variations in base metal concentrations (Zn+Cu+Cd+Pb) versus ground and surface water pH, New World district, Mont. Water data from SCS Engineers (1984). Classification scheme modified from Ficklin and others (1992).

fractures. Primary sulfide minerals persist as the main source of metals in sediments derived from tailings; these sediments contain as much as 1.9 weight percent lead, 6.2 weight percent zinc, and 279 ppm cadmium (Larocque and others, 1995).

Soil, sediment signatures prior to mining

Soil sampling has been proven useful as an exploration tool for delineating exploration targets for gold-bearing skarn systems. Hastings and Harrold (1988, fig. 7) showed that ranges for selected trace elements in rocks and soil at the Beal gold-skarn(?) deposit generally overlap. Arithmetic means for trace element concentrations in soil samples are similar to means for rock samples with the exception of gold (0.05 ppm in soil, 1 ppm in rock). Means for both soil and rock for arsenic, copper, and zinc at the Beal deposit are between 10 and 100 ppm; soil appears to be slightly enriched in arsenic and zinc relative to rocks.

The geology of the McCoy gold-silver-copper skarn deposit is shown in figure 3, along with contoured distributions of a number of metals (copper, arsenic, and gold) in soil samples. The operations at Cove, Nev., which are part of the mineralized system at McCoy, were the leading producer of silver in Nevada in 1994. The data illustrate the pre-mining distribution of metals, that is, background (natural concentrations of elements in natural materials that exclude human influence) geochemistry for soil in the area (fig. 3). These data were collected during exploration for the present McCoy mine, prior to large-scale mining (figure 3 provided by Echo Bay Minerals, written commun., 1995). Soil in the general area of the McCoy, Nev., gold skarn deposit includes as much as 15 to 20 ppm arsenic and as much as 200 to 300 ppm copper (fig. 3*C-D*). At McCoy, an area as much as 750 m wide contained soil with more than 5 ppm arsenic prior to large-scale mining. Analyses of the minus-80-mesh fraction of 140 soil samples in the general area of the copper-gold-silver West orebody, Copper Canyon, Nev., reveal that the soil is alkaline (pH typically 9.0 to 9.6). Calcite was present in about one-third of the samples (Theodore and Blake, 1978). Contents of silver, arsenic, gold, copper, lead, and mercury in soil above skarn are generally anomalous. Median values are: 3 ppm silver, 0.15 ppm gold, 150 ppm copper, 50 ppm lead, and 0.7 ppm mercury. Mercury contents in the soil appear to be higher along some traverses just outside or beyond the surface projection of underlying ore. Arsenic is >160 ppm in some soil samples. These are natural concentrations, uncontaminated
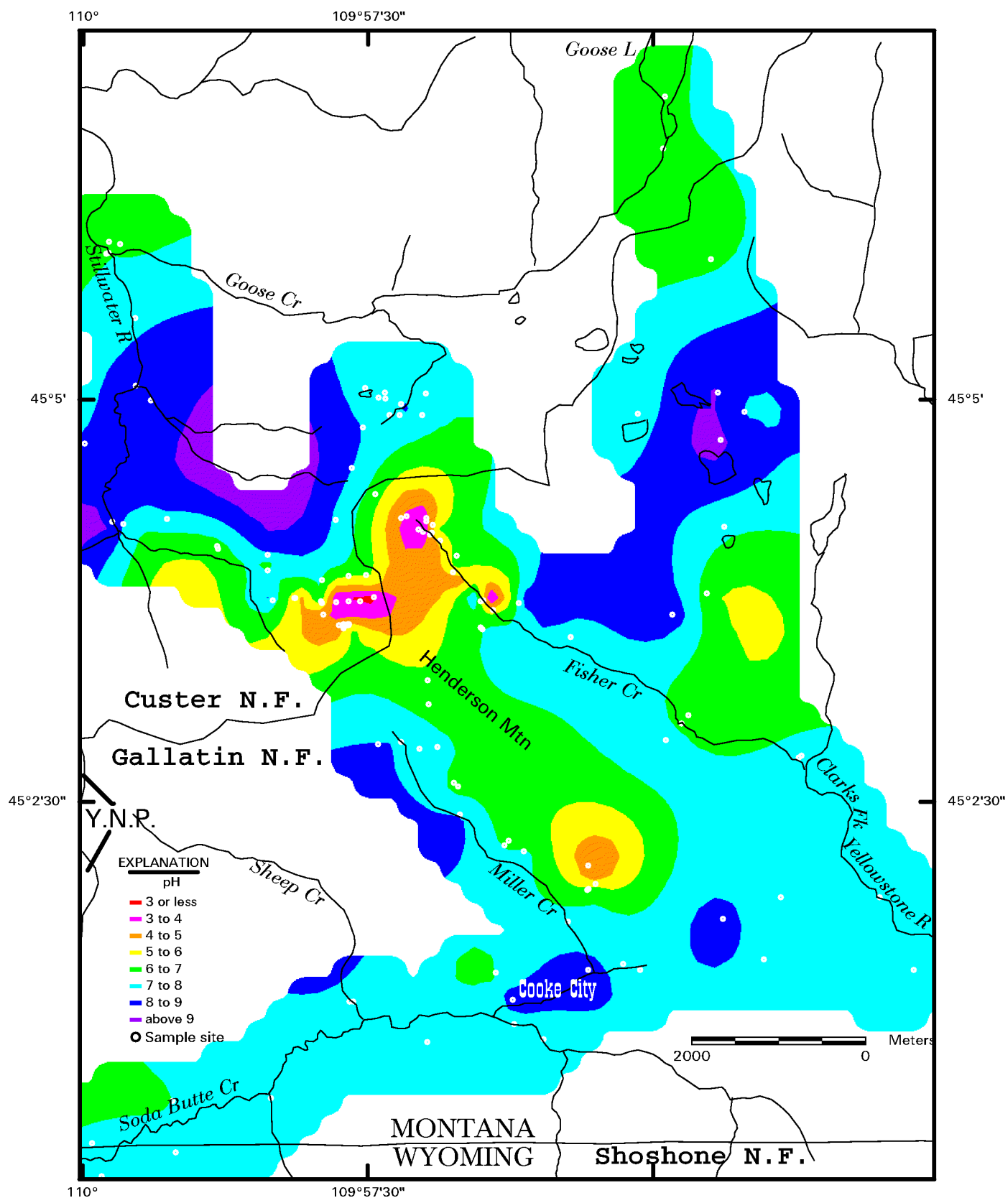
Figure 7. Contoured pH ranges in surface and ground water of the New World, Mont., districct (R.R. Carlson andd G.K. Lee, unpub. data, 1995).

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by mining activities.

The contrast between arsenic abundances in soil at the McCoy (15 to 20 ppm) and West (>160 ppm) orebodies shows that similar deposits in similar geologic and climatic conditions can have distinctly different geochemical signatures. Although these two deposits formed in different carbonate strata, in different tectonic blocks, both are copper-gold-silver skarn deposits associated with 39 Ma granitoid intrusions in north-central Nevada and both deposits are in arid-climate settings (Bailey and others, 1994) where precipitation averages 100 to 300 mm and elevations range from 1,200 to 3,000 m.

Potential environmental concerns associated with mineral processing
Poor site selection for tailings piles or mineral processing operations, leach pads, and settling ponds can lead to chemical (acid or metal loading) or physical (increased turbidity or sedimentation) degradation of surface and ground water and soil. Potential problems associated with cyanide heap leach operations include leach solution overflow during heavy rains and rapid snowmelt, liner failures in pads or ponds, and inadequate neutralization of cyanide solutions and cyanide-treated heap-leach pads at mine closure (Norman and Raforth, 1995). Free cyanide degrades naturally by volatilization, especially at elevated temperatures with ultraviolet radiation in solutions enriched in dissolved oxygen or CO_2. These favorable conditions may not obtain in areas where winters are long and severe, or in ground water. In such cases, heap detoxification may be accomplished by a variety of chemical or biological processes.

Smelter signatures
Copper smelters release SO_2 gas and represent the largest single source of arsenic emission from industrial processing of non-ferrous metals (Loebenstein, 1994). Flue dusts from copper smelters commonly contain lead, zinc, arsenic, and other metals. Copper concentrations in air near copper smelters may be elevated from normal abundances of a few to 200 ng/m^3 to abundances on the order of 5,000 ng/m^3. Smelters (copper, zinc, and lead) in the United States have been regulated for emissions and metal effluents since the mid 1970s.

Climate effects on environmental signatures
The effects of various climatic regimes on the geoenvironmental signature specific these deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-alt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics
Multispectral remote imaging over sparsely vegetated areas can help identify oxidized mine tailings. Ongoing heat evolution associated with sulfide mineral oxidation can be identified by airborne infrared surveys. Electromagnetic or direct current resistivity surveys can be used to identify and track metal-contaminated ground water flowing from tailings or mine shafts. Self potential, shallow seismic, and electrical surveys can be combined to provide information on the thickness, structure, and possibly the presence of oxidation-reduction centers associated with tailings and mine waste.

Examples of case studies of the environmental impact of skarn deposits
New World district, Mont.: Mine tailings from historic mining in the New World district have been washed downstream during large floods and especially during failure of the McLaren mine tailings impoundment along Soda Butte Creek in 1950 (Meyer, 1995). The site is along Soda Butte Creek, not at the McLaren mine itself, which is a few km to the north. The site has been investigated by EPA for remediation of acid mine drainage (SCS Engineers, 1984). Redeposited sand to clay-size sediment thins from a 35 cm-thick layer near the tailings failure to a layer a few cm thick 30 km downstream; lead and copper abundances in sediment decrease (from 1,200 to 300 ppm) downstream (Meyer, 1995). Preliminary studies of soil samples from meadows downstream from the tailings indicate patchy areas of low soil pH (3.5 to 4.0), low species diversity, and high abundances of toxic elements (Stoughton, 1995). Water data collected for the EPA site investigation are summarized above (see section entitled

"Drainage signatures).

Ok Tedi, Papua New Guinea: A number of recent studies address behavior of metals discharged in particulate form directly into the Fly River from mine tailings from the Ok Tedi porphyry copper and copper-gold skarn deposit (Salomons and Eagle, 1990; Apte and others, 1995). Mine tailings enter an upper tributary of this large tropical river because high rainfall and site instability preclude construction of adequate waste-retention structures. In water draining this area, calcium and bicarbonate ion concentrations are elevated because of abundant carbonate rock in the drainage area; bicarbonate ions buffer pH levels. Copper solubility is controlled by high concentrations of dissolved organic carbon and high alkalinity of the system; copper largely remains in particulate form (Salomons and Eagle, 1990). Copper-enriched sediment that is transported to an estuarine environment interacts with water having a different chemistry (greater concentrations of magnesium, calcium, and sodium) that leads to cation exchange reactions and release of copper in soluble forms.

Effects of metals associated with these deposits types on life

Plants: Copper is an important nutrient for plants; low soil copper contents (<10 ppm) may stress vegetation whereas high copper contents may be toxic.

Animals: Copper, iron, and zinc are essential elements for all animals. The effects of metals on animals depends on the bioavailability of metals ingested, and therefore, on the behavior of the metals in soil, plants, and water. Elevated metal concentrations in soil and plants, especially lead and arsenic can cause chronic toxicity. Metal deficiencies in ruminate animals are well-documented. Regional stream sediment geochemical surveys have been used in Great Britain to explore possible relations between geochemical environment and disease in animals due to inorganic element deficiencies or excesses (Bowie and others, 1985). The effects of metals are complex, because chemically similar elements, or elements that share metabolic pathways, may interact in the digestive tract. Absorption of copper as a nutrient, for example, can be inhibited by intake of high concentrations of zinc, cadmium, molybdenum, sulfur, iron, or silver and result in a copper deficiency syndrome.

Humans: Copper compounds in air, water, soil, sediment, and rocks are generally not harmful to humans because copper is strongly bound to soil or particles, or incorporated in insoluble minerals. Soluble forms of copper released into rivers and lakes are readily sorbed to particles. Copper is essential for human health and is not known to be a carcinogen (Agency for Toxic Substances and Disease Registry, 1989). Although cadmium is extremely toxic to animals and plants (as little as 1 to 10 ppm cadmium affects plant growth), much cadmium also apparently enters the human environment in cigarette smoke (Francis, 1984).

PERSPECTIVE

The following commentary is generally applicable to all three skarn-related geoenvironmental models.

Extensive buffering capacity afforded by limestone suggests that skarn deposits should be less likely point sources of acid mine drainage than many other deposit types. The efficacy of limestone as a natural mitigant for acid mine drainage depends on its availability and on economic considerations. Some limestone is commonly present near most skarn deposits, but some roof pendants in granitoids, originally composed of limestone, are completely converted to skarn. In many skarn deposits, calcite and other minerals, such as epidote and chlorite, characteristic of propylitic alteration are disseminated or vein gangue minerals in ore zones. These minerals also increase the ability of the host rock to consume acid (Smith and others, 1994).

In their study of factors controlling acidity and metal concentrations in water draining mines developed in various types of mineral deposits in Colorado, Plumlee and others (1993) showed that important factors include acid-uffering capacity of ore deposit gangue minerals and host rocks, types and abundances of sulfide minerals and their exposure to weathering processes, and availability of dissolved oxygen. No skarn deposits were included in their study; however, their results, with regard to variations in aqueous base-metal concentrations as a function of pH for high-sulfide mineral, carbonate-hosted deposits and low-sulfide mineral carbonate-hosted deposits, represent the most appropriate available analog for predicting mine drainage signatures for skarn deposits. The length of time that sulfide-mineral-bearing deposits are exposed to oxidation may play a significant role in their eventual contribution to local, undisturbed environments as well as environments disturbed by mining. Some originally sulfide-mineral-earing skarns have been thoroughly oxidized as a result of having been exposed during the last 35 million years.

Many mineralized skarn deposits are point sources for metals within much more widely altered mineralized systems, particularly porphyry systems. Some mineralized skarns may have potential for significant acid mine water development. However, none of the 61 mining-related sites on the Environmental Protection Agency (1995) National Priority List (Superfund) include skarn deposits. A number of skarn deposits, however, appear on lists of legal cases

that resulted from reported environmental damage (SCS Engineers, 1984). These include deposits where historic mine tailings contribute to water quality degradation and, in some cases, affected aquatic life. The extent of degradation from historic mining appears to be related to the magnitude and duration of operations as well as deposit type and climate. Any area that was extensively mined for long periods of time is likely to have experienced some environmental impact.

Skarn deposits that enter production today cannot be compared with skarn deposits worked a hundred, or even twenty, years ago. Many currently active mining or exploration projects involving skarn deposits operated at some time in the past at a smaller scale and are currently being re-evaluated for different metals (gold, silver) than were sought in past enterprises. Many abandoned or inactive skarn deposits are the focus of recent exploration because of economic changes or development of modern technology that allows previously uneconomic ore to be mined. For example, skarns that were mined in the past for base metals or tungsten may now constitute exploration targets for gold. Known or potential environmental hazards from historic mining can, in some cases, be mitigated by reopening the site to mining activity that involves reprocessing historic tailings using modern mining practices.

REFERENCES CITED

Andrews, R.D., 1975, Tailings-Environmental consequences and a review of control strategies, *in* International conference on heavy metals in the environment, Symposium proceedings, v. 2, Toronto, 1975, p. 645-675.

Apte, S.C., Benko, W.I., and Day, G.M., 1995: Partitioning and complexation of copper in the Fly River, Papua New Guinea: Journal of Geochemical Exploration 52, p. 67-79.

Agency for Toxic Substances and Disease Registry, 1989, Public Health Statements.

Bailey, R.G., Avers, P.E., King, Thomas, and McNab, W.H., eds., 1994, Ecoregions and subregions of the United States: U.S. Department of Agriculture Forest Service, 2 sheets, Scale 1:7,500,000.

Beus, A.A., and Grigorian, S.V., 1977, Geochemical exploration methods for mineral deposits: Wilmette, Illinois, Applied Publishing Ltd., 287 p.

Bowie, S.H.U., and Thornton, I., eds., 1985, Environmental geochemistry and health, Boston, D. Reidel Publishing Company, 140 p.

Brooks, J.W., Meinert, L.D., Kuyper, B.A., and Lane, M.L., 1991, Petrology and geochemistry of the McCoy gold skarn, Lander County, Nevada, *in* Raines, G.L. and others, eds., Geology and ore deposits of the Great Basin, Symposium Proceedings, Geological Society of Nevada, Reno, p. 419-442.

Broxton, D.E., 1979, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Billings NTMS quadrangle, Montana, including concentrations of forty-three additional elements: U.S. Department of Energy Open-File Report GJBX-150(79), 200 p.

Cox, D.P., 1986, Descriptive model of Zn-Pb skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 90.

_____1992, Descriptive model of distal disseminated Ag-Au deposits, *in* Bliss, J.D., ed., Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, p. 20-22.

Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Cox, D.P., and Theodore, T.G., 1986, Descriptive model of Cu skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 86.

Doebrich, J.L., Wotruba, P.R., Theodore, T.G., McGibbon, D.H., and Felder, R.P., 1995, Field trip guidebook: Trip H- Geology and ore deposits of the Battle Mountain Mining District, Humboldt and Lander Counties, Nevada: Reno, Nevada, Geological Society of Nevada and U.S. Geological Survey, Geology and ore deposits of the American Cordillera, 92 p.

Einaudi, M.T., and Burt, D.M., 1982, Introduction: terminology, classification, and composition of skarn deposits: Economic Geology v. 77, p. 745-754.

Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits: Economic Geology 75th Anniversary Volume, p. 317-391.

Emmons, D.L. and Eng, T.L., 1995, Geologic map of the McCoy Mining District, Lander County, Nevada: Nevada Bureau of Mines and Geology Map 103, scale 1:12,000, 12 p.

Environmental Protection Agency, 1995, National priorities list for uncontrolled hazardous waste sites (40 CFR Part 300): Federal Register, v. 60, no. 79, April 25, 1995, p. 20330-20353.

Ettlinger, A.D., and Ray, G.E., 1989, Precious metal enriched skarns in British Columbia: An overview and geological study: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Mineral Resources Division, Paper 1989-3, 128 p.

Ficklin, W.H., Plumlee, G.S., Smith, K.S., and McHugh, J.B., 1992, Geochemical classification of mine drainages and natural drainages in mineralized areas, *in* Kharaka, Y.K., and Maest, A.S., eds., Water-rock interaction: Seventh International Symposium on Water-Rock Interaction, Park City, Utah, July 13-18, 1992, Proceedings, v. 1, Rotterdam, A.A. Balkema, p. 381-384.

Francis, B.M., 1994, Toxic substances in the environment: New York, John Wiley and Sons, Inc., 360 p.

Glass, N.R., Arnold, D.E., Galloway, J.N., Henry, G.R., Lee, J.J., McFee, N.W., Norton, S.A., Powers, C.F., Rambo, D.L., and Schofield, C.L., 1982, Effects of acid precipitation: Environmental Science and Technology, v. 15, p. 162A-169A.

Hastings, J.S., and Harrold, J.L., 1988, Geology of the Beal gold deposits, German Gulch, Montana, *in* Schafer, R.W. and others, eds., Bulk minable precious metal deposits of the western United States: Geological Society of Nevada, Symposium Proceedings, April 6-8, 1987, Reno, NV, p. 207-220.

Johnson, T.W., 1991, Geology, hydrothermal alteration, and Cu-Ag-Au skarn and replacement mineralization in the

Stoughton, Julie A., 1995, The spatial distribution of grasses, soils, and trace elements along the floodplains of Soda Butte Creek, Montana and Wyoming: Geological Society of America Abstracts with Programs, v. 27, no. 4, p. 57.

Theodore, T.G., 1969, Surface distribution of selected elements around the Copper Canyon copper-gold-silver open-pit mine, Lander County, Nevada: U.S. Geological Survey Open-File Report, 21 sheets.

Theodore, T.G., and Blake, D.W., 1975, Geology and geochemistry of the Copper Canyon porphyry copper deposit and surrounding area, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-B, 86 p.

_____1978, Geology and geochemistry of the West ore body and associated skarns, Copper Canyon porphyry copper deposits, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-C, p. C1-C85.

Theodore, T.G., Orris, G.J., Hammarstrom, J.M., and Bliss, J.D., 1991, Gold-bearing skarns: U.S. Geological Survey Bulletin 1930, 61 p.

Torrey, C.E., Karjalainen, H., Joyce, P.J., Erceg, M., and Stevens, M., 1986, Geology and mineralization of the Red Dome (Mungana) gold skarn deposit, North Queensland, Australia, *in* Macdonald, A.J., ed., Proceedings of Gold '86, International Symposium on the Geology of Gold: Toronto, Geological Association of Canada, 1986, p. 3-22.

Van Gosen, B.S., 1994, Genesis of the Homestake Breccia Au-Ag-Cu deposits, New World district, Cooke City, Montana: Golden, Colorado School of Mines, M.S. thesis, 158 p.

White, D.E., Hem, J.D., and Waring, G.A., 1963, Data of Geochemistry-Chapter F. Chemical composition of subsurface waters: U.S. Geological Survey Professional Paper 440-F, 67 p.